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NASA Technical Paper 1553

Demonstration of Wetland Vegetation Mapping in Florida From Computer-Processed Satellite and Aircraft Multispectral Scanner Data

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SUMMARY

The Environmental Protection Agency and the National Aeronautics and Space Administration coordinated a project to assess the usefulness of satellite and aircraft multispectral scanner data for wetland vegetation inventory on the southwestern coast of Florida. A semiautomated, computerized technique was implemented to process multispectral scanner digital data. The cost-effectiveness of the classified vegetation maps was evaluated. Results indicated that mangrove communities were classified most cost-effectively by the Landsat technique, with an accuracy of approximately 87 percent and at a cost of approximately 3¢ per hectare compared to $46.50 per hectare for conventional mapping methods.

INTRODUCTION

The Environmental Protection Agency (EPA) and the National Aeronautics and Space Administration (NASA) launched a cooperative project in the fall of 1975 to test the use of remote sensing to inventory a part of the Florida wetlands. Vegetation classifications were derived from satellite and aircraft multispectral scanner (MSS) data by a technique developed at the NASA Earth Resources Laboratory (ERL) in Slidell, Louisiana; all data were processed at the ERL. Region IV of the EPA, located at Athens, Georgia, engages in the environmental analysis and surveillance of the U.S. southeast, and participated in the initial planning, ground truth, and evaluation of the final results.

The study area encompassed a section of the southwestern coast of Florida below 26° N latitude, including a part of Big Cypress Swamp, where subtropical vegetation blends into the natural landscape. The vegetation ranges from the upland freshwater system of cypress, swamp hardwoods, wet prairie grasses, and pine/palm hammocks to the transitional zone of marsh grasses that grades into the mixed mangrove forest fringing the coastline. (A list of Florida plant species encountered during the project and photographs of the Florida mangroves are included in the appendix.)

The EPA especially emphasized its need to remotely identify the mangrove communities, which are extremely difficult to survey on foot. The agency also was interested in remotely monitoring the invasion of melaleuca, a tropical tree, into disturbed Florida cypress swamps and the proliferation of Australian pine (not a true pine), an exotic tree escaped from cultivation.

The swamps of Florida are typical of those found in other locations; however, the presence of royal palm in communities of pine and/or hardwoods is unique to this state. The formation of pine/palm hammocks is a curious yet identifiable feature related to the calcareous soil of this area. Mangroves, although growing along portions of the Texas, Louisiana, and Mississippi coasts, thrive best along the Florida coast below 25° N latitude where they may reach a height of 30 meters (100 feet). The EPA was particularly interested in remotely identifying the mangrove forests within this study area; therefore, these species will be described and discussed in more detail.

Three different species comprise the 1748 square kilometers (675 square miles) of mangrove communities of all Florida estuaries, where the brackish waters represent the best growth conditions (ref. 1). According to Kuenzler, one of the best mangrove developments is in the Ten Thousand Islands region, included in the study area of this project. Here the mangrove forests extend inland for 29 or more kilometers (18 miles) along the water courses. Red mangrove, *Rhizophora mangle*, considered the pioneer species, roots into the marl soil below low tide level. The young plants require quieter water and a more stable substrate than the mature trees

(ref. 2). Matured red mangrove inhabits the slightly higher intertidal peat soil inundated by high tide, forming impenetrable forests with its maze of prop roots. Black mangrove, *Avicennia germinans*, occupies flat areas inundated by higher tides. White mangrove, *Laguncularia racemosa*, appears less frequently than the other two species, but favors a more inland environment, overlapping with the habitat of black mangrove and grading into the inland marsh.

The three species do not grow in habitats exclusive of one another. On the contrary, most of the mangrove forest in the Ten Thousand Islands appears as mixed associations of all three types. Pure red mangrove occurs only as a narrow band (less than 50 meters wide) interfacing coastal waters. In the inland situation, black mangrove is the only species that dominates in large communities to the exclusion of the other two species.

As residential and commercial development expands into these pristine mangrove forests, the mangrove ecosystem and its high natural productivity are threatened. In the overall scheme, the environmental balance is at stake because the mangroves, an important link in the food chain, may be removed or at least disturbed, causing a decrease in nutrient resources available to marine organisms. Therefore, an inventory of the mangroves, to the species level if possible, would serve as essential information required by the EPA to make management decisions concerning the Florida environment.

In compliance with the NASA's publication policy, the original units of measure have been converted to the equivalent value in the Systeme International d'Unites (SI). As an aid to the reader, the SI units are written first and the original units are written parenthetically thereafter.

PURPOSE

The purpose of this project was to produce vegetation maps from computer-processed MSS data acquired by both Landsat and aircraft. Then, the EPA would assess the usefulness of the remotely sensed maps and related technique to

1. Inventory vegetation communities and land use

2. Monitor wetlands for stress and changes, as a function of time, from manmade and natural causes

3. Define wetland boundaries in the Florida coastal zone study area

According to the EPA/Region IV, an inventory of marine wetlands would serve to

1. "... define areas where permits must be adequately protective of uniquely sensitive and productive environments"

2. "... define areas where non-point source controls should be adequately maintained to protect these environments"

3. "... define areas where dredge-and-fill activities (especially finger canal development) must be very carefully controlled"

4. "... define areas where construction grants for sewers in upland areas of the drainage basin must be diverted to other basins to protect the critical environment in the lower part of the basin"

Evaluation of the cost-effectiveness of the technique was also a prime objective. Consideration of the classification accuracies of the map products, their usefulness, and the cost to complete them constituted the criteria for evaluation.

APPROACH

Delineation of Study Area

The study area, a section of the southwestern coast of Florida, was selected for its high-density mangrove forests fringing the coastline and for its diversity of inland wetland vegetation. The area includes three urban centers: Fort Meyers marks the northwestern corner; Naples is located at the center west edge; and Marco Island appears in the southwest. The area to the east is relatively undeveloped but urbanization is anticipated, which is why a regulatory agency such as the EPA is interested in acquiring a practical technique for baseline inventory.

Training Sample Selection From Photography

As a first step in the remote-sensing technique applied in this project, a photomosaic of the study area (fig. 1) was produced from aerial, color-infrared photographs obtained by the state of Florida in 1971-1972. This photographic representation helped to discriminate the different vegetation

types existing in the study area, based on color tones and textures. These plant types were then marked on the aerial photographs for possible use as training samples in the computer processing of the Landsat and aircraft MSS data. The aerial photographs also served as a "field map" to locate the training samples during the ground truth mission.

Samples used for the classification of the Landsat data measured at least 300 by 300 meters (1000 by 1000 feet), while those used for the aircraft data classification measured at least 40 by 40 meters (120 by 120 feet). The minimum size of the training samples is related to the resolution capability of the respective scanners and to the need to assure statistical validity.

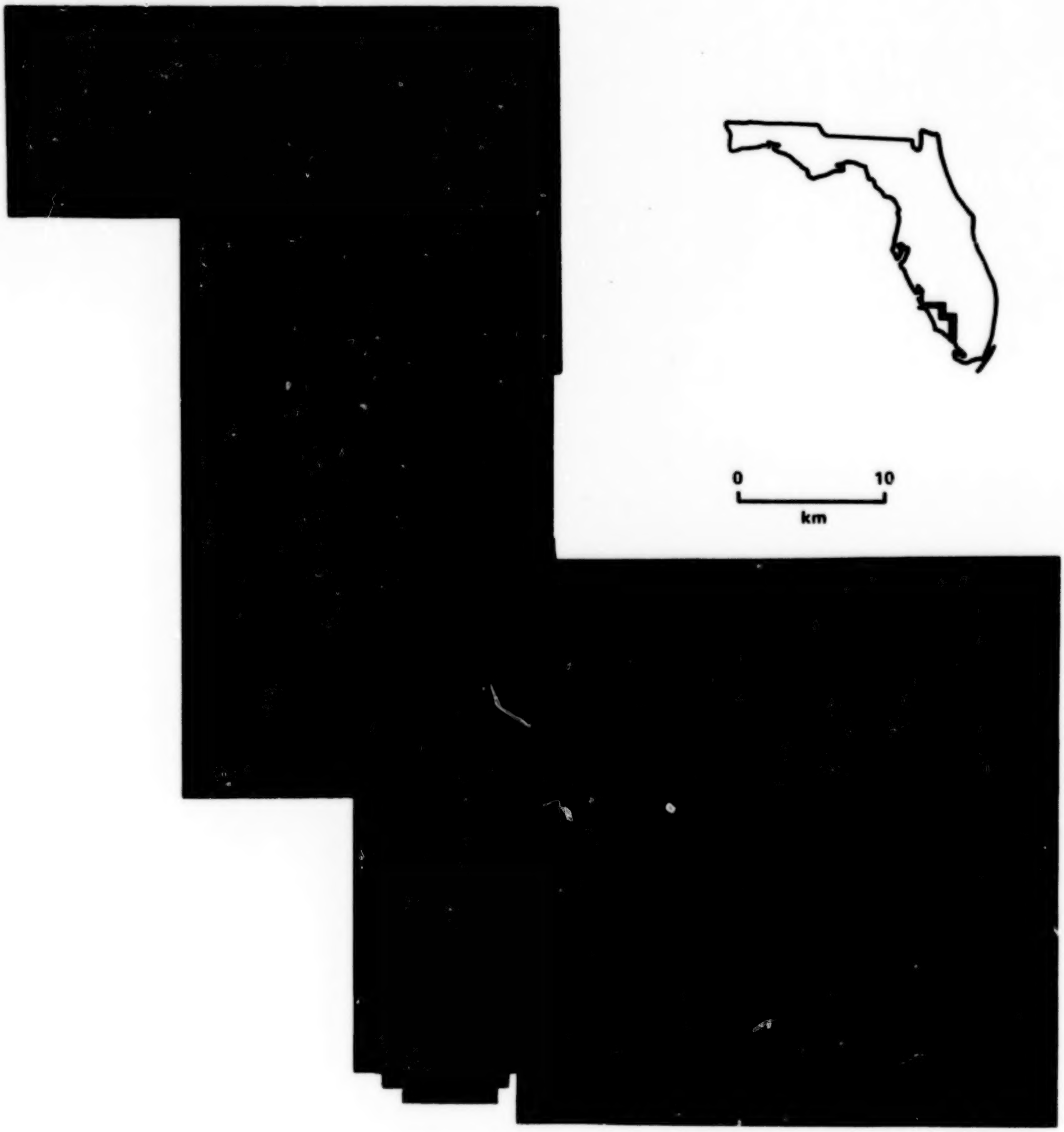


FIGURE 1.—Mosaic of aerial color-infrared photography of study area.

Ground Truth Mission

After the NASA and EPA investigators selected training samples to represent the full range of plant communities inhabiting the study area, they planned a ground truth mission to observe each sample by helicopter. One hundred sixty-three training samples were covered in 5 days of helicopter observation (September 15 to 19, 1975). The field team recorded a description of each sample, with the following observations made while hovering over the sample:

1. Percent of mud or water and its spatial distribution
2. Percent of total vegetation
3. Percent of each species in the total vegetation and the spatial distribution of each
4. Percent of crown closure, if forested
5. Percent of each species in the canopy, if forested

Aircraft and Satellite Multispectral Scanner Data Acquisition

The ERL aircraft acquired the MSS data on September 18, 1975, at an altitude of 3.0 kilometers (10 000 feet) over two overlapping, parallel flight lines, each 24 kilometers (15 miles) in length. The coverage is shown in figure 1. The flight mission was scheduled to coincide as closely as possible with the ground truth mission so that field observations correctly described the vegetation at the time of MSS data acquisition.

The flight lines covered the full distribution of vegetation types in a portion of the study area designated by the EPA to require finer resolution for the vegetation analysis. The aircraft deliberately flew at a time when the Sun's rays were parallel to the flightpath, thus minimizing distortion of the MSS data caused by an oblique Sun angle. The atmosphere was clear at the time of the flight.

The ERL multispectral scanner simulates the Landsat 1 and 2 scanners in the bandwidths of detected radiance. The instruments record energy in wavelengths of 0.5 to 0.6, 0.6 to 0.7, 0.7 to 0.8, and 0.8 to 1.1 micrometers. The aircraft scanner resolves at 2.5 milliradians, which means the instantaneous field of view, or pixel, measured 7.6 meters (25 feet) at a 3.0-kilometer altitude. The instrument scans a swath perpendicular to the line of flight and $\pm 50°$ of nadir.

The ERL obtained computer-compatible tapes of satellite MSS data from a Landsat-1 pass on November 2, 1975 (frame 5197-14383), which covered the study area. Cloud cover prevented the use of any pass acquired earlier in the summer/fall period. Spectral data collected during the peak of the summer growing season, before senescence, would have been desirable.

The Landsat scanner detects energy in the four bandwidths mentioned previously. The resolution cell size measures 56 by 79 meters (185 by 260 feet), approximately an acre, as the instrument passes over the Earth at an altitude of 920 kilometers (570 miles) with a scanning swath of approximately $\pm 6°$ of nadir.

Computer Processing of MSS Data

Because both the aircraft and Landsat MSS data existed in digital format, they could be classified quickly by computer via a pattern recognition technique developed at the ERL (ref. 3). In the initial step, the computer produced multispectral "signatures" for the training samples and used them to identify each cell of the raw scanner data. Specifically, the computer program determined the mean reflectivity response and standard deviation for each of the four bandwidths of data representing each sample. Samples of the same vegetation type were statistically grouped to produce a final mean reflectivity and variation about the mean.

After the program computed the spectral signatures for all classes, it used them to classify each digital element based on maximum likelihood theory. In multidimensional space, each spectral mean and standard deviation defined a volume of space representing that class type. Some classes intersected in space. The program then fitted each element of the entire data set against the multidimensional limits of each class. The element fitted with one of the classes when the likelihood (probability) was maximum that it belonged to that class. In this manner, most elements were classified. When the reflectivity responses of an element did not fit any of the spectral signatures developed from the training samples, the element remained unclassified.

The Landsat and aircraft classifications were produced in the same manner—but independent of one another.

Accuracy Verification Procedure

The accuracy of previous Landsat classifications derived from MSS data with the ERL technique has approximated at least 80 percent (ref. 4). However, accuracy varies with diversity, spatial arrangement, type of ground cover, and the verification procedure. The diversity of vegetation and the limited areal extent of plant communities, except for the mangroves, within the Florida study area suggested that a highly accurate classification might be difficult to obtain. Consequently, a test was designed to evaluate the accuracy of the Landsat wetlands classification.

First, a computer program designated verification test fields by unstratified, random sampling. In effect, the computer randomly selected approximately 100 elements from the Landsat classification, without regard to class identity. Each of these elements became the center of a 5 by 5 digit element box, or 25-element square test field. The computer outlined these test fields on the final color-coded classification and on a digitized, high contrast image of the raw data. A film recorder reproduced the color-coded classification and raw data image. The latter was used as a map for locating each test field during the verification mission by helicopter. The test fields were plotted on an unrectified image so that the evaluation of classification accuracy would not include any resampling error possibly introduced in georeferencing the Landsat MSS data.

During the verification mission, the helicopter, at an altitude of 50 to 150 meters (165 to 495 feet), approached each test field from its southern boundary. Thus, each test field had the same orientation during the observations. The field team diagramed the arrangement of the ground cover and identified it on a sheet of paper with a 5 by 5 unit grid representing the 5 by 5 classified elements, or 10-hectare (25 acre) test field. Later, EPA investigators compared the observations recorded on the gridded sheet to the computer classification within each 5 by 5 element box. They measured by planimeter the area drawn to represent each plant community and calculated it in terms of equivalent units of the 25-unit grid. Thus, one could directly compare the classified data in the 25-element box to the field observation of that site recorded in the 25-unit grid.

Cost Analysis of the Remote-Sensing Technique

The NASA investigators determined an approximate cost for using remote sensing to inventory the study area. The determination included the costs for acquisition, processing, analysis, and presentation of the aircraft and Landsat data. This cost analysis covered the classification of approximately 10 000 scan lines of aircraft data over approximately 400 square kilometers (150 square miles) and two computer-compatible tapes of Landsat data over approximately 4000 square kilometers (1500 square miles). The results do not imply a cost figure per scan line or per tape. The classification of additional aircraft or Landsat data would not increase costs proportionately because many of the items, once accounted, would not be repeated in the classification of additional data. The analysis used receipts or catalog prices to derive the costs of materials, services, and travel and lodging expenses within the project area. Transportation expenses to and from the site were excluded. The project records and support contractor job orders dictated labor costs. Where possible, project costs reflected separately the costs associated with aircraft data and those associated with Landsat data.

RESULTS

Description of Training Samples

Table I provides brief descriptions of the training samples that were "ground truthed" by helicopter September 15 to 19, 1975. The ground-truth team actually visited 163 samples, of which 27 represented variations in water.

Aircraft MSS Classification

Within the area covered by the two flight lines of MSS data, 45 training samples were "ground

truthed" and then incorporated in the pattern recognition software. Training sample statistics defined the multispectral "signatures" for all vegetation types. The processing of the scanner data through the ERL classification software was standard except that a separate computer search classified water based on two channels of data, one in the visible spectrum and one in the near-infrared spectrum. The computer used all four channels to identify all other classes. Only the data within the middle 90° of each flight line were accepted for classification, though the full scan width was 100°.

TABLE I.—Florida Training Sample Data Grouped According to Similar Composition

[Each number identified an individual sample and its location for record keeping.]

Grouping	*Sample numbers*
Mixed *Avicennia germinans*, *Laguncularia racemosa*, *Rhizophora mangle*	1, 3, 5, 6, 33, 34, 36, 37, 65, 66, 69, 71, 96, 97, 100, 102, 103
Mixed *Laguncularia racemosa*, *Rhizophora mangle*	2
Mixed *Rhizophora mangle*, *Avicennia germinans*	95, 133, 134
Mixed *Rhizophora mangle*, *Avicennia germinans*	4
Mixed *Avicennia germinans*, *Laguncularia racemosa*	101, 122
Avicennia germinans > 70%	35, 38, 63, 64, 65, 70, 121
Rhizophora mangle	125
Distichlis spicata > 60%	7, 43, 44, 68, 105, 107, 115, 120
Spartina spartinae > 60%	8, 9, 10, 11, 13, 19, 118
Juncus roemerianus	104, 106, 112 (?)
Mixed marsh grasses: codominants: *Spartina* sp., *Juncus roemerianus*, *Eleocharis microcarpa*, *Distichlis spicata*	32, 48, 68, 73, 114
Wet prairie—Saw blade sedge (unidentified)	14, 22, 25, 39, 52
Sagittaria sp. > 50%	92
Typha latifolia	31, 113
Native grasses and *Taxodium distichum* sparsely distributed	80
Taxodium distichum > 50%	20, 28, 40 (?), 46, 49, 50, 67, 72, 78, 89, 90, 111, 117
Mixed lowland hardwoods with *Taxodium distichum* < 50%	17, 18, 21, 23, 27, 29, 45, 62, 85, 86, 116, 119
Lowland hardwoods: Codominants: *Quercus virginiana*, *Magnolia*, *Acer rubrum*, *Sabal*, *Myrica cerifera*	16, 27
Mixed *Pinus elliottii*, *Taxodium distichum* < 50%, and/or palms	26, 27, 42, 47, 55, 57, 59, 60, 75, 78, 81, 88, 98, 99
Marsh grass and *Pinus elliottii* sparsely distributed	123
Mixed palms > 50%	51, 56, 82
Mixed *Sabal* and *Taxodium distichum* < 50%	24, 27, 29, 42, 45, 47, 54, 62
Mixed palms and *Pinus elliottii*	53, 58, 61, 77, 79, 82, 83, 110, 124
Salix nigra > 50%	84, 91, 93
Melaleuca	130
Brazilian pepper = 80%	12
Casuarina equisetifolia > 60%	131, 132
Submergent vegetation	76
Water	126, 127, 128, 129, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 155 to 163
Barren areas	153, 154

The map product resulted from the mosaicking of the classified data from the two flight lines originally recorded at an approximate scale of 1:24 000, but reduced here for reproduction in figure 2.

The map legend describes the final classification. Within most of the mangrove forest, the black, red, and white species (*Avicennia germinans, Rhizophora mangle*, and *Laguncularia racemosa*) occurred in such evenly mixed stands that they could not be multispectrally separated and were coded dark green. However, in some cases, black mangrove grew in areas large and pure enough to be distinctly classified and was coded light green. Though red mangrove frequently grew along the swamp periphery interfacing with the coast, it occurred in such narrow bands that the scanner could not resolve it. The areas coded light brown and designated as Spartina marsh represented marsh dominated by either cord grass, *Spartina spartinae*, or black rush, *Juncus roemerianus*, because these two species had a low probability of separability from one another. Salt grass marsh, coded gold, represented areas dominated by *Distichlis spicata* with *Salicornia* spp. and *Batis maritima* as subdominants.

The pink color indicated the presence of cypress swamp; it represented a somewhat variable ecological condition from areas of 100 percent cypress (*Taxodium distichum*) and of differing crown closures to areas of cypress co-dominated or subdominated by lowland hardwood species (live oak, *Quercus virginiana*; wax myrtle, *Myrica cerifera*; sweet bay, *Magnolia virginiana*; palmetto, *Sabal* spp.; pine, *Pinus elliottii*). Barren and urban areas and clouds have similar high reflectivities; therefore, the computer classified them all as one class (it was coded white) Brazilian pepper trees, *Schinus terebenthifolius*, were recorded as pale blue. The forest category, coded red, included areas dominated by live oak and wax myrtle and subdominated by sweet bay and palmetto. The dark blue code designated areas classified as pure cattail marsh, *Typha latifolia*.

Black identified all unclassified surface features. This included shadows created by overhead clouds, as well as all other vegetation and areas of water for which representative training samples were lacking.

The vegetation classification displays the natural gradation of mangrove forest adjacent to the coast, through the more inland saline marsh, which interfaces the cypress swamp and lowland hardwood forest. The known natural trend of the vegetation supports, in general, the trend presented by the classification map. One source of confusion occurred as an "edge effect" where the growth of mangrove peripheral to either coastal beach and water or to marsh grass, in some cases, resembled the multispectral signature for cypress swamp.

Landsat MSS Classification

The Landsat-1 frame 5197-14583 of November 2, 1975, the first nearly cloud-free pass of the summer-fall growing season, was selected for classification. Only tapes 3 and 4 (of a 4-tape set) were used, which constitutes the eastern half of the frame. A computer program initially corrected the raw data for a repetitive sixth scan line interference (attributed to the satellite scanner system) by replacing the relative reflectivity count values in every sixth scan line with the average count for each of the four channels in the preceding set of five scan lines. The computer generated a visual display tape for each band of data; however, the display tape for band 6 was used more than any other for the process of geographically locating the training samples onto the Landsat data. The locations of the training samples were transferred from the aerial color-infrared photographs to the multispectral bulk data according to scan lines and element numbers. One hundred thirty-four of the vegetation training samples that had been "ground truthed" in September and 20 more water samples were transferred to the Landsat display data.

Training samples were then either accepted or rejected based on the generated statistics of mean, standard deviation, and covariance matrix for each band of data for each training sample. The pattern recognition software relied on those training samples approaching normal distributions to classify the remaining data. It was desirable, although not always possible, to formulate training statistics for a given class using at least two or three samples. The relative probability of separating one class from another, or "interclass pairwise divergence," predicted possible conflicts in separation for some of the classes, which will be explained in the following paragraphs.

The initial classification attempted to identify nearly all cover types, even those that occurred in areas of a size that might have been stretching the limit of Landsat resolution. The later verification data suggested a broader level of classification was a more realistic goal. Consequently, of an original 17

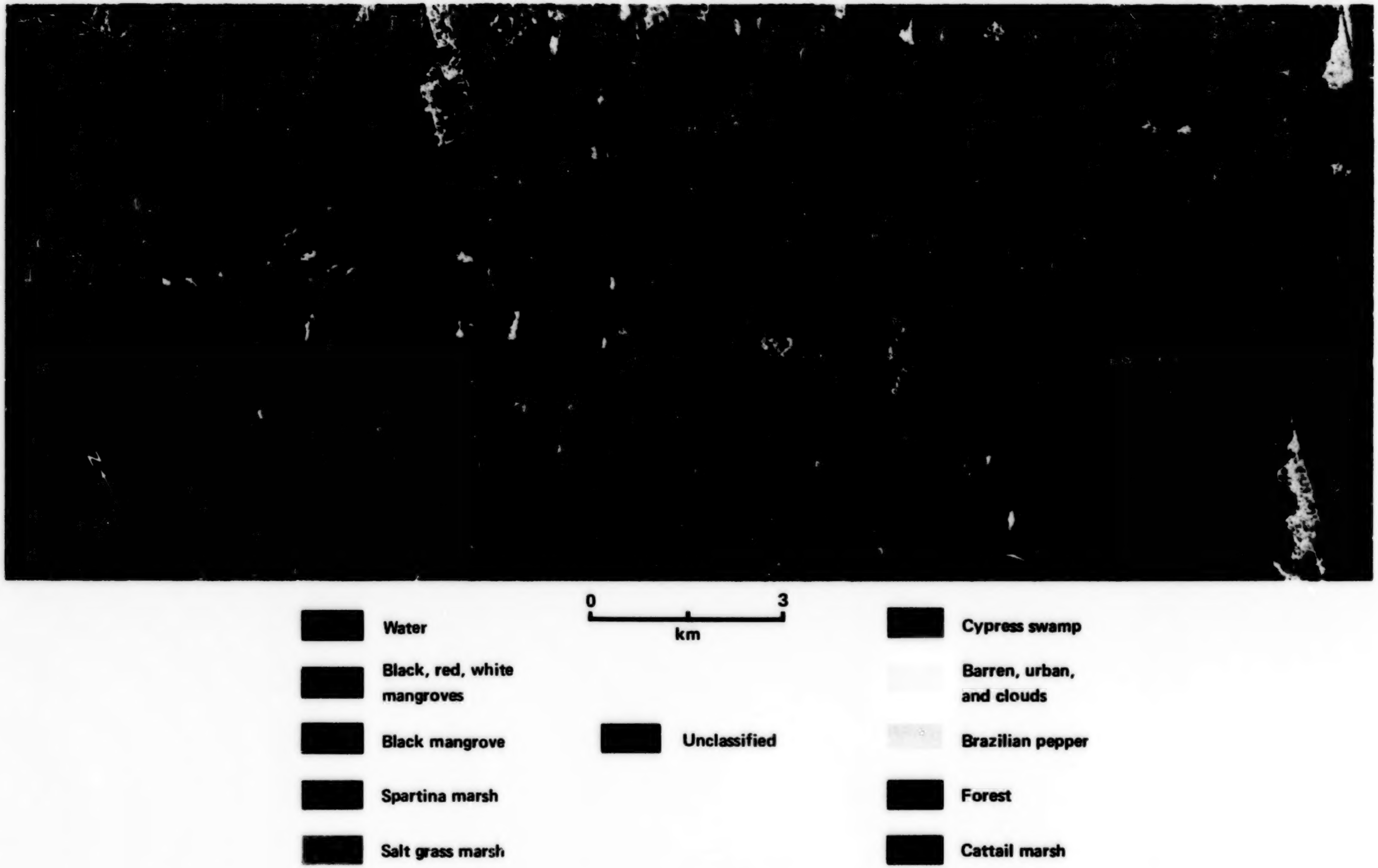


FIGURE 2.—Aircraft MSS classification of the vegetation in the Ten Thousand Island area.

classes, some were grouped to produce a second and final classification of 11 classes as listed in figure 3.

The map legend (fig. 3) explains the color representation for the various classes. The water class, coded dark blue, included clear coastal water, as well as shallow, sediment-laden areas. The satellite scanner could not resolve red mangrove, which fringed the coastline in a narrow band. Large, interior, homogeneous areas of black mangrove, coded light green, were discriminated from mixed mangrove associations, coded dark green. Even in a pure stand of black mangrove, there was some contamination by the other species; therefore, the spectral signatures for the two mangrove classes were similar. This contributed to a classification accuracy that was lower for the two individual classes, but higher when the two classes were considered together.

The salt grass category was coded orange and was dominated by the presence of *Distichlis spicata* growing with sea-blite, grasswort, and batis just behind the mangrove swamp. Cord grass and black rush (both salt marsh species) and wet prairie grasses (composed of freshwater grasses and sedges) were collectively termed wetland grasses and coded turquoise. The naturally occurring communities of mixed wet prairie grasses distributed under sparsely-grown cypress were difficult to categorize.

Brazilian pepper, a shrub unique to the Florida peninsula, was coded violet and appeared as an isolated, but prominent, 1- to 2-hectare (3 to 5 acre) stand north of Everglades City. Inland stands dominated by palm with lesser amounts of buckbrush and wax myrtle were coded lime-green.

The mixed cypress swamp was a major inland community, coded yellow, and included cypress, cypress/mixed lowland hardwoods, cypress/slash pine and/or willow in varying proportions. A major conflict occurred between spectrally similar mangrove stands and what was thought to be particularly dense stands of mixed lowland hardwoods codominant with cypress. Because the habitats of mangroves and fresh swamp are nearly mutually exclusive, a computer program to automatically correct the problem areas was implemented to improve the classification.

Areas of Australian pine, slash pine, and pine/palm hammocks were coded brown and occurred adjacent to the fresh swamp and wet prairie groups. The slash pine in the study area was observed to grow sparsely, perhaps 20 to 30 percent crown closure, with exposed understory grasses and sometimes palm. Melaleuca, a cultivated species lately introduced to the area but now escaped, was coded white.

Unclassified areas were coded black and represented phenomena for which no training samples were selected, as in the case of urban, agricultural, and barren areas and the potholes and clouds and cloud shadows to the north. They also represented areas where the reflectivities varied greatly from the statistical acceptance curves developed from the training samples.

In summary, the Landsat technique distinguished the important ecosystems of the area. The Fahkahatchee Strand, a cypress, hardwoods, mixed pine and palm swamp, shows up prominently inland in figure 3. The classification identified water as a significant component of the Strand. The Corkscrew Swamp, a mixed cypress ecotype east of Naples, is visible on the map. The greater density of pine forest and shrubs/palmetto, indicative of higher topography and drier soil, appeared as expected in the northern region of the scene. Generally, the predominant classes of fresh swamp, pine, grasses, water, and mangrove separated well from one another except for the conflict between fresh swamp and mangrove. The mutual exclusion in habitats of these two classes resolved the conflict.

Verification of the Florida Wetlands Landsat Classification Accuracy

Computer software randomly selected the verification test fields and outlined them on a high-contrast Landsat image derived from bands 2 and 4 (fig. 4). By scaling-off significant features on this image, the helicopter team gauged the approximate location of each field.

The accuracy evaluation ultimately included only those fields located within the area for which the computer was "trained." Thus, the check consisted of 104 fields. The EPA initiated the verification mission approximately 1 year after the date of the Landsat pass.

The computer printed out a character plot giving the classification of each of the 25 elements within each field outlined on the Landsat classification.

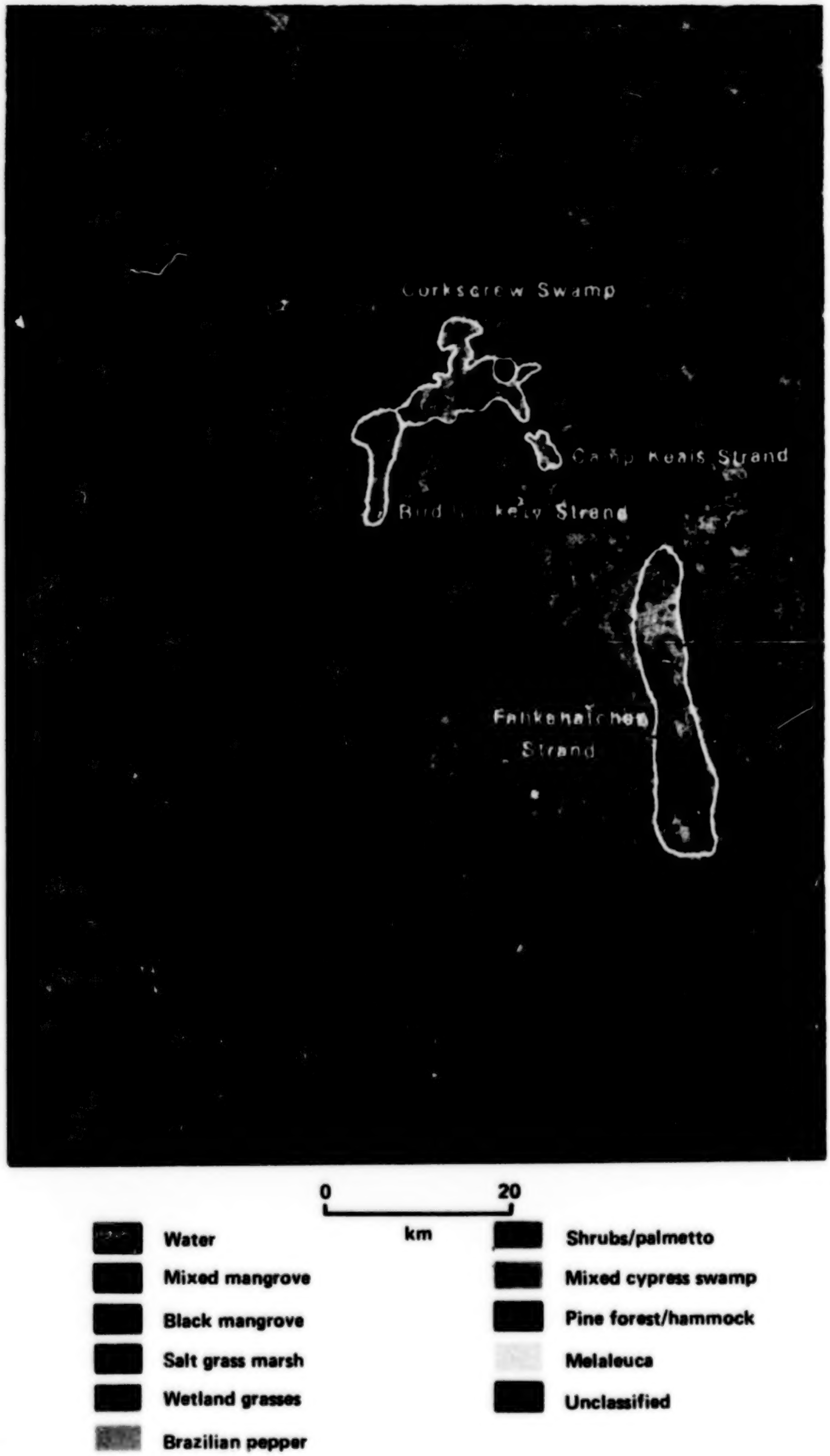


FIGURE 3.—Landsat MSS classification of the study area indicating noteworthy cypress strands and swamps and their apparent composition.

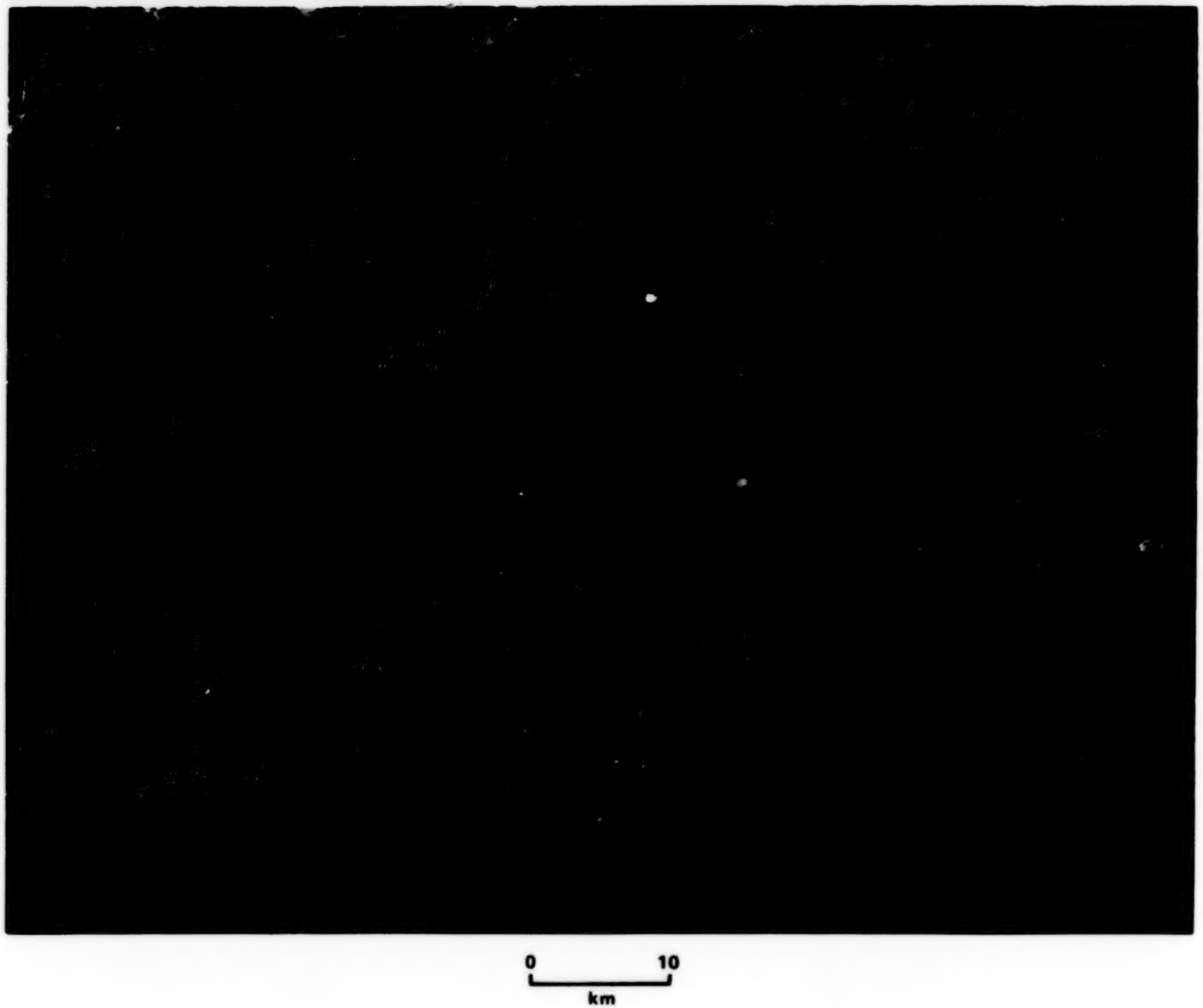


FIGURE 4.—Landsat raw-data display indicating locations of randomly selected verification test fields (yellow boxes.)

An alphabetical letter represented each of the 23 classes in the character plot. However, similar classes were combined to give the following groups (table II): (1) water, (2) mangroves, (3) salt grass, (4) wetland grasses, (5) Brazilian pepper, (6) shrubs/palmetto, (7) cypress swamp, (8) pine, (9) melaleuca, and (10) unclassified. Using these groups, the classification was compared to the actual ground data grid with its accompanying evaluation for a typical test field (fig. 5).

To explain the evaluation, let G represent the 25-unit grid on which the ground data were recorded during the helicopter verification mission. Let P represent the 25-digital element character plot of the classified Landsat data for the same test field. First, the data on G were identified and grouped in the same way as the data on P, so that the same vegetation categories could be compared. The number of equivalent units taken up by each group on G was calculated from planimeter measurements. The number of units of a group on G was compared to the number of elements indicated for that same group on P. That number which was coincident to both G and P was recorded for each group. These numbers were summed for all groups in each field. If the sum represented a majority of the elements within the test field, then the test field was counted as correctly classified. The EPA performed the identifications, measurements, and calculations for all verified test fields.

Assuming the criteria in the preceding paragraph, the average accuracy of the Landsat classification for all classes was 74 percent (table III). Mangrove, the special interest category, had a Landsat classification accuracy of 87 percent. The aircraft classification was 68 percent accurate for all classes.

TABLE II.—Florida Wetlands Landsat Classes Combined for Evaluation

Major group	*Combined Landsat classes*	*Landsat classification alphabetical code*[a]
Mixed mangrove	Red mangrove	D
	Black mangrove	E,F
	Mixed mangrove	G
Salt grass	Salt grass	H
Wetland grasses	*Spartina/Juncus*	I
	Typha/Eleocharis	J
	Wet prairie	K
	Sagittaria	V
Brazilian pepper	Brazilian pepper	L
Shrubs/palmetto	Shrubs/palmetto	M
Cypress	Cypress	N
	Mixed cypress	O
	Pine/mixed cypress	P
	Willow	W
Pine	Pine/palm	Q
	Mixed pine	R
	Pine	S
	Australian pine	U
Melaleuca	Melaleuca	T
Water	Water	A,B,C

[a]Used in character plot shown in figure 5.

Cost Analysis Results Provided by NASA ERL

Table IV summarizes total costs for the demonstration project, initiated in late 1975 and completed in late 1976, except for costs incurred by the EPA analysis of the verification mission. Itemized costs for project planning, data acquisition, data processing, and verification are given in tables V to VIII, respectively. The costs do not reflect inflation that has occurred since the completion of the project.

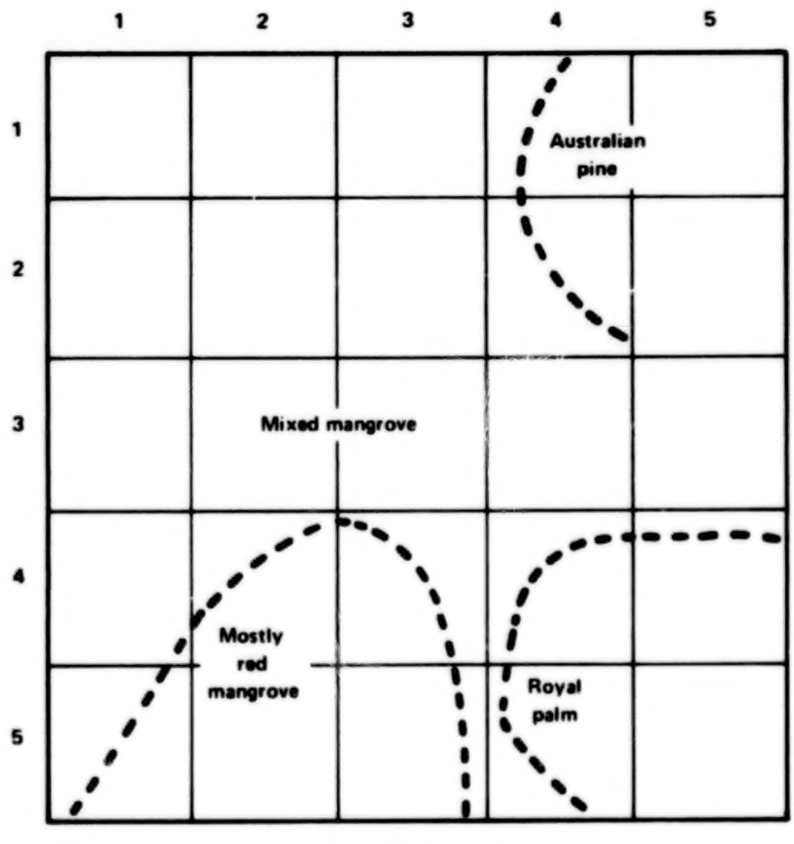
Separation of some of the costs for Landsat and aircraft project planning, data acquisition, and processing was not done at the time when costs were actually incurred. For instance, the project investigators did not convene to plan separately for Landsat and aircraft data processing. Therefore, many of these costs reflect only estimates. Table IX summarizes the data in tables IV to VIII and compares the estimated costs of this project had only aircraft or satellite data been used.

Cost-Effectiveness Evaluation Provided by the EPA[1]

The cost-effectiveness of this remote sensing mapping technique was determined by user requirements versus accuracy and cost. The remote identification of mangroves was the primary requirement, with other wetland communities of secondary interest.

The EPA determined the hypothetical cost to produce the vegetation classifications by conventional survey methods, and this cost was then compared to the cost of duplicating them by the remote-

[1]This section is a condensed version of the EPA's independent evaluation of the cost-effectiveness of this demonstration project.



Ground data grid G

	1	2	3	4	5
1	E	G	K	G	G
2	E	G	G	G	G
3	G	G	G	G	G
4	G	G	G	K	G
5	G	E	G	–	–

Landsat character plot P
(See table II for code)

	Observed (from G)	Landsat classification (from P)	Correctly classified
Black mangrove (E,F)	0	3	
Mixed mangrove (D,G)	19.75	18	18
Wet prairie (K)	0	2	
Australian pine	2.75	0	
Unclassified	2.50	2	2
Total	25	25	20

FIGURE 5.—Accuracy evaluation for test field number 186. Red mangrove appearing on *G* was included in the mixed mangrove category. Since a royal palm class was not developed, it fell in the unclassified category.

sensing technique (based on the cost analysis results). However, the EPA investigators stated they could not provide an accuracy for the conventional type of classification because they had never been required to perform an accuracy test. Thus, an accuracy comparison was not possible.

Table X itemizes the costs for conventionally mapping 80 hectares (200 acres) of a *Spartina* marsh and mixed mangrove forest, respectively.

Table XI provides the cost comparison of both methods, using the *Spartina* marsh and mangrove forest as examples. A Landsat map of either category costs 3¢ per hectare to produce; however, a conventional mangrove map costs approximately 1550 times more and for *Spartina*, approximately 550 times more.

According to the EPA, "Mapping a *Spartina* marsh with conventional techniques would probably be more cost-effective for less than 80 hectares. Larger areas of *Spartina* and any significant areas of mangroves would require remote sensing to be cost-effective." The mangrove forest itself is nearly impenetrable by conventional ground survey.

TABLE III.—Landsat and Aircraft MSS Classification Accuracies for the Florida Wetlands

Classification	*Number of verified test fields*	*Number of test fields accepted as correctly classified*	*Classification accuracy, percent*
Landsat:			
All classes	104	77	74
Mangrove class	31	27	87
Aircraft:			
All classes	16	11	68

TABLE IV.—Total Costs for the EPA/NASA Florida Wetlands Remote Sensing Project

Item	*Cost*
Project planning and preparation	\$4 125
Data acquisition	9 463
Data processing	7 850
Verification	1 460
TOTAL	\$22 898

TABLE V.—Itemized Costs for Project Planning and Preparation

Activity	*Costs of —*		
	Actual Landsat and aircraft project	*Projected Landsat project only*	*Projected aircraft project only*
Planning, supervision, and coordination			
NASA civil service (80 man-hours)	\$800	\$500	\$300
Support contractor (40 man-hours)	400	250	150
EPA (40 man-hours)	400	300	100
Mission preparation			
Labor (ERL support contractor):			
Photomosaic preparation (50 man-hours)	\$500	[a]\$0	[a]\$0
Selection of training samples (49 man-hours)	490	475	157
Mission package preparation (20 man-hours)	200	80	200
Literature search (80 man-hours)	800	[b]0	[b]0
Materials			
Reference book	\$24	[b]\$0	[b]\$0
Color infrared prints	500	500	500
Black and white prints	3	0	3
Maps and graphic supplies	8	8	8
Total	\$4125	\$2113	\$1418

[a]Photomosaic not considered necessary for general/production (non research-and-development) remote sensing exercises.
[b]Not considered necessary when field personnel are thoroughly familiar with test site.

TABLE VI.—Itemized Costs for Data Acquisition

Item	Costs of —		
	Actual Landsat and aircraft project	*Projected Landsat project only*	*Projected aircraft project only*
Satellite data			
Landsat tape	$200	$200	$0
Aircraft data			
Magnetic tape for RS-18 MSS	$260	$0	$260
Aircraft fuel and oil	383	0	383
9-inch color infrared film	261	0	261
Support contractor:			
Salaries (242 man-hours)	2430	0	2430
Expenses (food, lodging, transportation)	1216	0	1216
Ground truth data			
Support contractor:			
Salaries (40 man-hours)	$400	$388	$128
Expenses (food, lodging, transportation)	184	178	59
NASA civil service:			
Salaries (40 man-hours)	400	388	128
Expenses (food, lodging, transportation)	184	178	59
EPA:			
Salaries (80 man-hours)	800	776	256
Expenses (food, lodging, transportation)	368	356	118
Materials and services:			
Helicopter rental —			
Support contractor	493	478	158
EPA	884	857	283
Cataloging —			
Preparation of Herbarium samples and integration of data cards and ground truth forms into file system (100 man-hours)	1000	970	320
Total	$9463	$4769	$6059

TABLE VII.—Itemized Costs for Data Processing

Item	Costs of —		
	Actual Landsat and aircraft project	*Projected Landsat project only*	*Projected aircraft project only*
Landsat data			
Computer classification of data:			
NASA civil service (80 man-hours)	$800	$800	$0
Support contractor (200 man-hours)	2000	2000	0
Product preparation:			
Photographic laboratory	175	175	0
Graphics support (20 man-hours)	200	200	0
Aircraft data			
Computer classification of data:			
NASA civil service (80 man-hours)	$800	$0	$800
Support contractor (350 man-hours)	3500	0	3500
Product preparation:			
Photographic laboratory	175	0	175
Graphics support (20 man-hours)	200	0	200
Total	$7850	$3175	$4675

TABLE VIII.—Itemized Costs for Accuracy Verification[a]

[Site visitation by EPA]

Item	Cost
Salaries (48 man-hours)	$480
Expenses (food, lodging, transportation)	300
Helicopter rental	680
Total	$1460

[a]This effort is not considered necessary if the user has previously established the technique's accuracy to his satisfaction.

DISCUSSION

As stated earlier, this project was conceived jointly by the EPA and NASA to test the success of remotely mapping some of the wetland vegetation of Florida. For an inventory map, such as the one derived in this project, one desires the classification that most accurately describes the real land cover situation. However, what determines success is whether the classification results meet certain criteria, one of which should be a defined minimum accuracy. Another is affordable costs. Thus, the "user" has to identify his requirements.

Table XI clearly demonstrates the cost-saving benefit of using the remote-sensing technique. The EPA believed that an accuracy level of approximately 80 percent was required for a useful classification, and favorably acknowledged the 87 percent obtained for the mangrove class (table III).

In fact, the EPA used the Landsat classification to locate black mangrove basins for a research study of nutrient exchange between black mangroves and the surrounding estuaries and offshore areas. Also, based on the results of this study, the EPA has initiated an inventory of the mangroves along the entire coast of Florida (approximately 14 000 square kilometers) using the Landsat technique.

TABLE IX.—Comparison of Estimated Costs Using Only Landsat or Aircraft Data[a]

[Florida Wetlands Remote Sensing Project]

Item	*Landsat cost estimate*[b]	*Aircraft cost estimate*[c]
Project planning and preparation	$2 113	$1 418
Data acquisition	4 788	6 065
Data processing:		
NASA civil service	800	800
Other support work[d]	2 375	3 875
Subtotal	$10 076	$12 158
Accuracy verification[e]	1 460	1 460
Total	$11 536	$13 618

[a]Estimated costs based on defined size of project test area. The classification of additional airborne or Landsat data would not increase costs proportionately since many items, once accounted for, would not be repeated for additional data.

[b]Estimate based on a land area size of approximately 3885 square kilometers (1500 square miles).

[c]Estimate based on a land area size of approximately 389 square kilometers (150 square miles).

[d]Data processing item is similar in content to the service obtainable from private industry.

[e]This effort may not be necessary if the accuracy for the remote sensing technique has been previously established by the user to his satisfaction.

TABLE X.—Estimated Costs of Conventional Mapping Methods for a Spartina Marsh and a Mangrove Forest[a]

[80 hectares]

(a) Spartina marsh.

Item	*Cost*
Aerial photograph duplicates	$50.00
Study preparation (2 man-days)	146.00
Study (8 man-days)	534.00
Travel expenses	106.00
Transportation GSA[b]	50.00
Laboratory work (6 man-days)	438.00
Total	$1324.00
Cost/hectare	$16.50

(b) Mangrove forest.

Item	*Cost*
Aerial photographs	$50.00
Study preparation (4 man-days)	292.00
Study (10 man-days)	730.40
Travel expenses (10 man-days)	350.00
Transportation GSA	100.00
Laboratory work (20 man-days)	2191.00
Total	$3713.40
Cost/hectare	$46.50

[a]Computed by the EPA.

[b]GSA = General Services Administration.

TABLE XI.—Cost Comparison Between the Landsat and Conventional Classification Techniques

Technique	Class type of—	
	Spartina marsh, cost per hectare	Mangrove forest, cost per hectare
Landsat	$0.03	$0.03
Conventional	16.50	46.50

The classifications produced from this project were the result of a "first attempt" in processing MSS data of the study area from only a single date, and could be refined. The following paragraphs present (1) possible ways to improve the technique, (2) sources of error, and (3) specific problems encountered in this investigation.

The time of MSS data collection deserves consideration. The September date of the aircraft mission was still within the time frame of vigorous vegetative growth for most species, thus providing good data for spectral separation. However, the late November date of the Landsat pass may not have been good for spectral separation. By late fall, the annual leaf drop of some deciduous trees and the annual dying-back of marsh grasses, if they had been extensive, could have constrained the development of distinct and representative spectral signatures.

The "edge effect," referred to in the "Results" section of this report, created an initial misclassification in both the aircraft and Landsat processed data. A computer program corrected these areas of misclassification by automatically changing the designated pixels from the class in error to the appropriate class. In other words, the pixels that were initially classified as cypress along the boundary of much of the mangroves were then changed to mangrove. However, this is not a completely accurate fix. Each changed pixel actually represented the integrated spectral response of two cover types, the average of which happened to approximate the spectral response of a third cover type—cypress, in this case.

The "edge effect" is a universal problem in the processing of digital data. It is manifested in the delineation of agricultural fields and urban areas, in particular. The need exists to develop software to (1) identify each edge pixel and (2) classify it according to the identity of the cover type occurring in the highest proportion within the pixel.

The aircraft and Landsat data were classified into similar categories. However, the aircraft classification, which includes the coastal Ten Thousand Islands area, represented only a section of the entire Landsat study area. Some of the training samples incorporated in the aircraft classification, when they met the minimum resolution size requirements of Landsat, were also incorporated in the satellite classification. However, other training samples, of necessity, were selected to represent other vegetation types growing within the Landsat coverage but not included in the aircraft study area. The use of a set of training samples common to both classifications was not feasible; therefore, a one-to-one comparison of each class for the two classifications was not possible. The higher resolution of the aircraft scanner provided more detail in the classification of the vegetation communities and other surface features, but the resolution of the Landsat classification was considered adequate for the identification of the majority of the classes.

Australian pine and melaleuca, two exotic species gone wild in the Florida landscape, were not successfully identified with the Landsat technique. The melaleuca has invaded the cypress and hardwood swamps and seems to be competing so successfully that it seriously endangers that ecosystem. It was hoped that Landsat data could be used to monitor the presence of melaleuca as the initial step in controlling its distribution. However, after the field verification, it became apparent that although the melaleuca was widespread, it existed in communities too small to develop a signature for Landsat classification. The technique successfully classified Australian pine only when it occurred in extensive areas, which was infrequent. Therefore, it was grouped with pine. Neither melaleuca nor Australian pine grew in the aircraft study area. In 1981, when NASA launches Landsat D with its thematic mapper of 30-meter resolution, the spatial limitations of the present technique will be reduced.

The final design of the accuracy verification test combined practical and statistical considerations. The percentage of the budget designated for the verification mission dictated the number of test fields that could be verified by helicopter, considering the rental fee. Even with the budget restrictions, approximately 100 fields (25 elements each) provided an adequate number for statistical analysis.

Geographic uncertainty was a potential source of error in the verification test. If, in verifying a test field that spatially represented a square of 25 digital elements, the position of the hovering helicopter was offset by one element in one direction, the potential misclassification was interpreted as 5/25 or 20 percent. If offset by one element in both the forward and lateral directions, the interpreted misclassification for the test field was 9/25 or 36 percent. This would be due to positional uncertainty at the time of verification, and might have caused the conclusion of a lower classification accuracy. The study area did not have many surface features to make site identification easier.

A suggested refinement in the verification method, viewed in retrospect, involves the diagraming of the ground cover in each test field based on helicopter observations. With flight time at a premium, each ground diagram was completed as quickly as possible. This amounted to a rather rough sketch in some cases. The areas within the sketched boundaries were then measured by planimeter. In essence, the method of measurement was unnecessarily precise for data that were collected in a less precise way. The results could be improved with more accurate diagrams.

CONCLUSIONS

In a cooperative project, the NASA/Earth Resources Laboratory and the EPA/Region IV applied a NASA remote-sensing technique to meet an EPA objective to inventory the Florida wetlands. The study area included a part of Big Cypress Swamp and the Ten Thousand Islands, an untouched area dominated almost exclusively by mangroves and pressured by residential and commercial developers. The EPA evaluated the technique for its utility in monitoring the mangroves, in particular. The agency also assessed the cost-effectiveness of the technique. The following conclusions address classification results and the EPA evaluation, respectively.

The following conclusions refer to technical aspects of the Landsat and aircraft multispectral scanner classifications:

1. The major vegetation classes identified by the remote-sensing technique were cypress swamp, pine, wetland grasses, salt grass, mixed mangrove, black mangrove, and Brazilian pepper.

2. Australian pine and melaleuca were not satisfactorily classified from Landsat. These escaped species, though of high environmental interest, only infrequently occurred in stands large enough to be detected with the data used for this project.

3. The aircraft scanner provided better resolution resulting in a classification of finer surface detail. However, Landsat scanner resolution was considered adequate for most of the classes of interest.

4. With both Landsat and aircraft-acquired data, the mangroves were successfully identified.

5. An "edge effect," created by the integration of diverse spectral responses within boundary elements of digital data, affected the wetlands classification. A solution to the "edge effect," which occurs in other surface classifications, as well, should be investigated.

6. The aircraft classification accuracy, averaged for all classes and based on 16 test fields over the 400-square-kilometer study area, was 68 percent.

7. The average accuracy of the Landsat classification for all classes was 74 percent based on 104 test fields over a 4000-square-kilometer project area. Mangroves classified at an accuracy of 87 percent.

The following conclusions refer to the evaluation of the usefulness and cost-effectiveness of the remote-sensing technique in view of the EPA requirements:

1. In comparing costs, inventory by the Landsat technique proved far cheaper than by conventional ground survey. Based on the 1500-square-kilometer study area, a mangrove map would cost approximately 3¢ per hectare using the Landsat technique. The same map would cost $46.50 per hectare using a conventional method.

2. For small areas less than 80 hectares that require wetlands inventory, Landsat resolution is too low. In this case, the EPA recommended the use of the aircraft scanner technique or conventional ground survey to produce a surface classification.

3. The EPA considered adequate the overall Landsat classification accuracy and the accuracy for the mangrove class. The EPA had no data from which they could compute an average accuracy for inventory by the conventional method.

4. The application of a technique is a measure of its usefulness. The EPA used the classification results to locate black mangrove basins in a separate

study of nutrient exchange between this species and the surrounding estuaries. Further, the EPA has initiated an inventory of the mangroves along the entire coast of Florida, implementing the Landsat remote-sensing technique outlined in this report.

Earth Resources Laboratory, NSTL
National Aeronautics and Space Administration
NSTL Station, Mississippi February 9, 1979
177-52-83-13

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Appendix

The following list includes the common names and Latin names of the Florida plant species encountered during this project. Figures 6 to 9 are photographs of Florida mangroves taken during the ground truth mission.

Common name	*Latin name*
Red mangrove	*Rhizophora mangle*
Black mangrove	*Avicennia germinans*
White mangrove	*Laguncularia racemosa*
Salt grass	*Distichlis spicata*
Cattail	*Typha latifolia*
Wet prairie	Mixed grasses & sedges (*Cyperus* sp.)
Brazilian pepper	*Schinus terebenthifolius*
Palm	*Serenoa repens*
Buckbrush	*Baccharis halimifolia*
Cypress	*Taxodium distichum*
Slash pine	*Pinus elliottii*
Melaleuca	*Melaleuca quinquenervia*
Australian pine	*Casuarina equisetifolia*
Bulltongue	*Sagittaria falcata*

Common name	*Latin name*
Willow	*Salix caroliniana*
Black rush	*Juncus roemerianus*
Cord grass	*Spartina spartinae*
Glasswort	*Salicornia virginica*
Sea-blite	*Suaeda linearia*
Batis	*Batis maritima*
Spike rush	*Eleocharis microcarpa*
Mixed lowland hardwoods	
Red maple	*Acer rubrum*
Sweet bay	*Magnolia virginiana*
Wax myrtle	*Myrica cerifera*
Sweet gum	*Liquidambar styraciflua*
Live oak	*Quercus virginiana*

FIGURE 6.—Inner estuary of mixed mangroves.

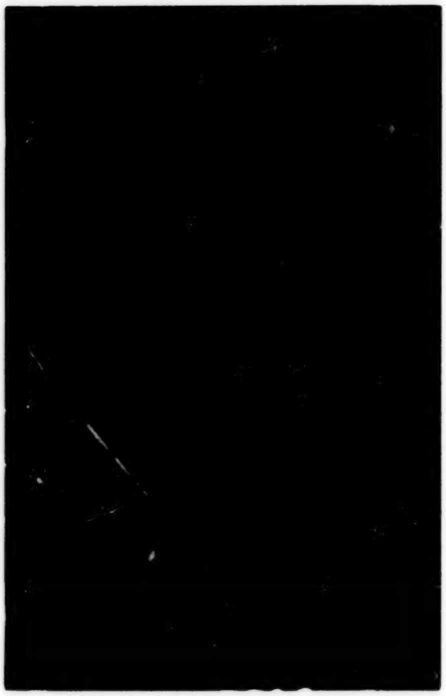

FIGURE 8.—White mangrove in fruit. Leathery leaves are common to all three mangrove species.

FIGURE 7.—Stand of red mangrove with prominent prop roots.

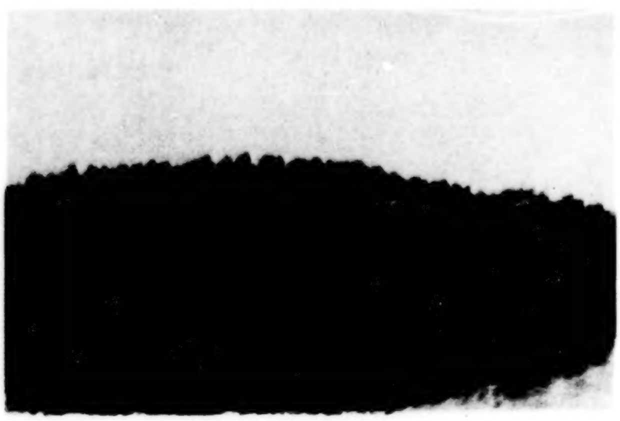

FIGURE 9.—Dense mixed mangrove forest fringing a coastal inlet.

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*The Earth Resources Laboratory is an element of the National Space Technology Laboratories, NSTL Station, Mississippi 39529.

16. Abstract

The procedures, technique, and cost data are given for a project sponsored jointly by the Environmental Protection Agency and the National Aeronautics and Space Administration to test the success of remotely mapping wetland vegetation of the southwestern coast of Florida. The joint project used a computerized technique to process aircraft and Landsat multispectral scanner data into vegetation classification maps. The cost-effectiveness of this mapping technique is evaluated in terms of user requirements, accuracy, and cost. Results indicate that mangrove communities were classified most cost-effectively by the Landsat technique, with an accuracy of approximately 87 percent and with a cost of approximately 3¢ per hectare compared to $46.50 per hectare for conventional ground survey methods.

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